AD/A-003 826

LOW POWER IMPACT VELOCITY AND ACCELERATION RECORDING SYSTEM WITH PIEZOELECTRIC INPUTS

Clive L. Nickerson

Army Natick Laboratories
Natick, Massachusetts

December 1974

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER 75-29-AMEL	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER AD/A-003 826
4. TITLE (and Subtitle) Low Power Impact Velocity and Acceleration Recording System With Piezoelectric Inputs		5. TYPE OF REPORT & PERIOD COVERED Technical Report
		6. PERFORMING ORG. REPORT NUMBER AMEL 75-29
7. AUTHOR(s) C. L. Nickerson		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Natick Laboratories Natick, Massachusetts 01760		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1J662708D552
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Natick Laboratories Natick, Massachusetts 01760		12. REPORT DATE
		13. NUMBER OF PAGES 34
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Recording Systems
Impact Velocity
Accelleration

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the development of two low power solid state signal conditioning units and associated piezoelectric transducers which when coupled with a previously developed magnetic tape recorder form a system used to measure and record the impact velocity and impact deceleration experienced by containers during shipment.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

PRICES SUBJECT TO CHANGE

TECHNICAL REPORT

75-29-AMEL

LOW POWER IMPACT VELOCITY AND ACCELERATION RECORDING SYSTEM WITH PIEZOELECTRIC INPUTS

By

Clive L. Nickerson

Aero-Mechanical Engineering Laboratory
U.S. Army Natick Laboratories
Natick, Massachusetts 01760

Approved for public release; distribution unlimited.

Citation of trade names in this report does not constitute an official indorsement or approval of the use of such items.

Destroy this report when no longer needed. Do not return it to the originator.

ic

FOREWORD

The original investigations of a Low Power Impact Velocity and Acceleration Recording System with Piezoelectric Inputs were conducted under Contract DA19-129-QM-2082 (OI 6150) by the Shock and Vibration Division of Mitron Research and Development Corporation with Mr. Maurice Gertel as Principal Investigator and Mr. David Franklin as Project Engineer. Project Officer and Alternate Project Officer for the U.S. Army Natick Laboratories were Mr. Matthew Venetos and Mr. Denis O'Sullivan, both formerly of the Engineering Sciences Division of the General Equipment & Packaging Laboratory. This contract was originally funded under Project 7X91-03-015 and later transferred to Project 1M643324D587.

Subsequent invesitigations, funded under Project 1J662708D552, were conducted by Mr. Clive Nickerson, Project Officer, formerly of the Engineering Sciences Division of the General Equipment and Packaging Laboratory and Mr. Frank Barca, Alternate Project Officer, of the Engineering Sciences Division of the Aero-Mechanical Engineering Laboratory. Technical and production assistance was furnished by the U.S. Army Electronics Command at Fort Monmouth, New Jersey.

TABLE OF CONTENTS

LIST OF FIGURES

LOW POWER IMPACT VELOCITY AND ACCELERATION RECORDING SYSTEMS WITH PIEZOELECTRIC INPUTS

I. INTRODUCTION

A. Background

Since 1962 NLABS has conducted a program of in-house and contracted efforts to develop the capability of measuring and recording various environmental hazards to which a container is subjected during shipment and handling. This program resulted in the development of a magnetic tape recorder unit and various transducers for use with this recorder for the measurement of drop height, temperature, humidity, and static and dynamic loads.

As a continuation of this program, NLABS developed the capability (Reference 1) of measuring acceleration values with the basic recorder unit. At the same time, a recording system that uses an accelerometer with a suitable cushioning device to provide an alternate drop height transducer with some weight and size advantages was developed.

The signal flow in both systems is from a set of three accelerometers to an electronics module and then on to a magnetic tape recorder of the type described in TR 72-72-GP (Reference 2). The accelerometers are mounted perpendicular to one another within a shipping container so as to determine impact magnitude regardless of package orientation upon impact. The recording range of the acceleration system is 5 g's to 1000 g's and will record the absolute value of shocks along the three principal axes of a container. Response is essentially flat between 10 Hz and 300 Hz, allowing accurate measurement of shocks within the 2 to 40 msec range which encompasses most typical impact surfaces.

The velocity transducer system is capable of measuring impact velocities equivalent to drop heights in the range of 8 cm to 120 cm. The system is designed so that the nature of impact surfaces does not affect the measured velocity (equivalent drop height). Typical impact surfaces are concrete, soil, and pallet decks. Unlike the acceleration system, this system uses bipolar recording. Package orientation upon impact can be determined.

The recording requirements differ markedly for the drop height and acceleration measurements. The input signals range from 4 to 1 for the drop height to 200 to 1 for the acceleration measurements.

The recording capabilities of magnetic tape when used in the stationary recording application dictate that different signal conditioning circuitry should be used in the drop height and acceleration measurements. The magnetic tape recording-playback theory and curves have been presented in Appendix B of Reference (2).

B. System Specifications

	Acceleration System	Velocity System
System Weight (Kg)	9.1	8.2
System Dimensions (cm)	41 X 31 X 24	41 X 31 X 24
Electronics Module Weight (Kg)	2.12	1.26
Electronics Module Dimensions (cm)	10.5 X 11.4 X 9.8	11.8 X 11.8 X 3.8
Measurement Range	5 g to 1000 g	8 cm to 120 cm
Frequency Response (Hz)	10 to 300	4 to 30
Temperature Range (°C)	−40 to 65	−40 to 65
Fragility (g)	250	250
Supply Voltage	±12	±6
Quiescent Current Drain (μ)	1300	700
Battery Requirements	Sixteen 1.5-volt Alkaline "C" Cells	Sixteen 1.5-volt Alkaline "AA" Cells

C. Elements Common to Both Systems:

1. Accelerometer:

A shear-type piezoelectric accelerometer is used for impact sensing. It is a miniature reliable device having a wide temperature range and the capability of responding linearly to inputs ranging from 5 to 1000 g's. A frame conforming to the dimension of a shipping carton is used to mount three sensing devices to obtain orthogonal components of the input shock. Rigid mounting is required in the case of acceleration measurement whereas the sensors are mounted on the end of cantilever springs to yield 10 Hz mechanical systems for velocity measurement. Features of the sensor are tabulated below.

Model	Endevco 2221D
Charge Sensitivity	17.0 pK p^C/pk g (nom.)
Transducer Capacitance (C_A)	700 pF (nom.)
Cable Capacitance (C_c)	300 pF (nom.)
Resonant Frequency	30 KHz
Resistance	20,000 Megohms
Charge Frequence Response	±5% 2 to 7000 Hz
Transverse Sensitivity	3%
Linearity	4% per 1000 g
Temperature Range	–54°C to 177°C
Dimensions	1.52 cm Dia X 0.8 cm
Weight	12 grams

2. **Charge Amplifier:**

A high-to-low impedance conversion must be performed on the accelerometer output so that operations may be performed without significant loading by moderate input impedance circuits. An operational amplifier with capacitive feedback (charge amplifier) is used as a first stage in both acceleration and velocity signal conditioning. A feedback value of 0.01 μF effectively "swamps" accelerometer plus cable capacity of approximately 0.001 μF. Low frequency response is improved by a factor of ten. Driving capability and insensitivity to input capacitance variation is also gained; however, voltage sensitivity is reduced by a factor of ten.

$$Q \text{ (Charge Sensitivity)} = 17.0 \text{ pC/g}$$

$$V \text{ (Voltage Sensitivity)} = \frac{Q}{C_A + C_c} (.1) = \frac{17.0 \text{ pC/g}}{1000 \text{ pF}} (.1) = 1.7 \text{ mv/g}$$

To prevent the open loop gain of the amplifier from driving the output to saturation in response to input offset, a parallel feedback resistor is used to deliberately sustain leakage. This resistor creates low frequency drop off. It has a value of 16 meghoms in the acceleration system yielding a pole at 1 Hz – well below the measurement range and thus having very little effect on the frequency response. In the velocity system the input is of constant frequency so a flat response is not essential. A resistance of 4.7 megohms is used to minimize voltage offset without reducing the 10 Hz output significantly. A pole is created at 3.39 Hz and the gain at 10 Hz is approximately 0.95 times that of mid-band gain.

3. **Operational Amplifiers:**

Signal conditioning circuitry in both the acceleration and velocity systems is built around microcircuit operational amplifiers because of their flexibility in manipulating analog signals and their high-to-low impedance conversion capabilities.

National Semiconductor NH0001 hybrid devices were used in the prototype system because of their low quiescent current drain. Monolithic micropower operational amplifiers are now available from most linear microcircuit manufacturers and could alternatively be used.

4. **Recorder Interface:**

Both the acceleration and velocity recording systems have as an integral component the magnetic tape recording unit described in TR 72-72-GP. This unit mates with the appropriate electronics conditioner via connector J1/J2 and the interface cabling carries control and signal lines from conditioner to recorder. Three signal lines convey conditioner data channel outputs to the recording head (Nortronics 5651) through current limiting resistors in the recorder.

The recorder advance control circuit has been incorporated into the conditioner. This circuit is a two-transistor switch that grounds an advance trigger terminal in the recorder after peak signal is reached. The triggering signal in the acceleration recorder is picked off from the non-inverting amplifier output in the shaping circuit. The velocity system trigger is a rectified amplified version of the record signal. Power (+45 V) to this circuit is supplied by the coupling cable from the recorder. Recorder and conditioner commons are also tied together by the interface cable.

5. **Packing:**

In use, the conditioning box may be strapped or taped to the recording unit and both cushioned on all sides with at least 5 cm of polyurethane foam. A frame conforming to the dimensions of the container is necessary to mount the transducers. This frame also serves to maintain the shape of the package and protect the system.

II. THE DROP HEIGHT SYSTEM

A. Transducer

The problem of using a cushioning medium in conjunction with measuring drop height by means of determining the velocity of impact or the maximum deceleration upon impact has been analyzed theoretically in a previous report, TR-67-50-GP, (Reference 3). The shock pulse on the container upon impact varies in period and intensity with the nature of the impact surface. For accuracy in drop height measurement, the period of the cushioned device must be long compared to the period of the shock which stops the container. At the same time, a longer period corresponds to a larger deflection and thus to a larger device size. In the report cited it was concluded that a 10 Hz frequency was a good compromise between a long period and the resultant large device size, and the higher errors resulting from a shorter period. At this frequency the longest half sine pulse acceleration that stays within 10% of linear drop height measurement is 40 msec. This duration is considered adequately longer than that experienced in the majority of field conditions.

The drop height transducer consists of an accelerometer mounted at one end of a flat spring used as a cantilever beam with the other end of the beam attached to the impacting container. Upon impact, the kinetic energy of the accelerometer is converted to potential energy in the spring system. The accelerometer indicates the maximum deceleration at maximum deflection of the spring; this output of the accelerometer is related to the initial drop height. The frequency of the spring system is adjusted to 10 Hz so that the period of the spring is long compared to the anticipated periods of the impact shocks; thus, the output of the accelerometer is largely independent of the nature of the impact surface. The transducer also puts out a higher frequency wave of about 100 Hz which tends to corrupt the 10 Hz primary response. An electronic filter (see IIB) is used on the output from the accelerometer which eliminates the high frequency wave without excessive attenuation of the primary signal. This filter, together with a 2.5 cm X 14.5 cm X 0.064 cm beam with an accelerometer and dummy weight on opposite sides of the end of the beam, provides signals easily related to impact velocity.

This spring device oscillates for several seconds. To be useful, damping is provided which brings the device to rest within two seconds. This damping was accomplished by taping two 2.5 cm X 2.5 cm X 10 cm hard rubber pads to either side of the beam.

The signal conditioning electronics provides for a blanking out of the signal to the recorder head for two seconds after the first input pulse maximum. Thus the device damping and electronic circuitry combine to insure that only one pulse is recorded on the tape per drop.

B. Electronics

An electronics package (Figure 1) housing the circuitry necessary to condition the velocity transducer signal is connected to the recording unit by a flexible cable. The electronics (Figure 2) are built around low power operational amplifiers; a pair are used for each velocity channel and an additional pair are used for precision rectifying of transducer signal to trigger tape recorder advancement. A total of eight amplifiers is then required and is supplied by an integral battery source.

The conversion of accelerometer charge output to voltage is done by an amplifier configured as a charge amplifier as described in Section IC and shown in Figure 2.

To eliminate the undesirable 100 Hz wave mentioned in Section IIA, the output of the charge amplifier is fed through a series of four passive single pole low-pass RC filters (R1-C1 on schematic). Following the filters is a high-pass combination (R11-C1) necessary to block d.c. resulting from current and voltage offset of the charge amplifier. All this is terminated by the non-inverting input of another amplifier with a mid-band gain of $(R_4 + R_3)/R_4$. More low-pass filtering is included with R3-C1. Capacitor C3 blocks amplification of the second amplifier's input offset. The overall flat-band gain of the amplifier is found by considering parallel capacitors as opens and series capacitors as shorts and is

$$\frac{R11}{R11 + 4R1}\left(1 + \frac{R3}{R4}\right) = \frac{42.2}{60.8}\left(1 + \frac{38.3}{511}\right) = 52.5 = A_{mid}$$

Attenuation of the signal by RC combinations may be found by

$$A(\text{gain}) = \frac{e_o}{e_{in}} = \frac{1}{\left(1 + \left(\frac{f}{f_c}\right)^2\right)^{1/2}} A_{mid} \quad \text{where } f_c = \frac{1}{2\pi RC}$$

Calculated and tabulated below are the velocity system element gain factors.

Circuit Element	Combination	f_c (Hz)	Response At 10 Hz	Response At 100 Hz
Charge Amplifier	R2-C2	3.39	0.951	1.000
Filter 1	R1-C1	34.3	0.96	0.324
Blocking Network 1	R11-C1	3.37	0.935	0.99
Filter 2	R3-C1	4.16	0.384	0.042
Blocking Network 2	(R3+R4)-C3	0.0186	0.99	0.99
Head Impedance	R/L	1.94K	1.0	1.0

Total Response at 10 Hz $= (0.951)(0.96)^4(0.935)(0.99)(0.384)\text{Amid}$

$= 0.289 \text{ Amid}$

Total Response at 100 Hz $= (1.00)(0.324)^4(0.99)(0.99)(0.42)\text{Amid}$

$= 0.00046 \text{ Amid}$

Response at 100 Hz $= 20 \log \frac{0.00046}{0.289} = -55.92 \text{ db}$

The 100 Hz wave is virtually eliminated by the time it reaches the recording head.

A rectified amplified version of the record signal is produced by a precision rectifying circuit which additively couples the outputs of the three channels to the recorder advance control circuit. Details about the rectifier appear in Section IIIB.

C. Calibration Series

Both before and after test shipments the instrumented container should be subjected to a series of calibration drops. The results of the calibration drops are used to interpret the data recorded during shipment. The following is a suggested calibration drop test plan:

1. Calibration Drop Test

(a) Drops shall be made from a free fall drop tester, if available, onto a rigid impact surface such as a concrete floor, steel plate, or hard-packed sand.

(b) Drops shall be as near to flat as possible.

(c) A minimum of four seconds shall be allowed between drops.

(d) The container faces ara designated in Figure 3.

(e) The drop sequence shall be as follows:

Table 1

Calibration Series

Drop Height (cm)	No. of Drops per Face	Drop Face Sequence					
30	3	2	3	5	4	1	6
60	3	2	3	5	4	1	6
90	2	2	3	5	4	1	6
120	2	2	3	5	4	1	6

For Example: Start at height of 30 cm and make 3 drops on Face #2, followed by 3 drops on Face #3, etc. When all the 30 cm drops are complete, go to 60 cm and make 3 drops on Face #2, followed by 3 drops on Face #3, etc.

2. Calibration by Voltage Insertion

The deceleration in g's felt by the piezcelectric element mounted on the velocity transducer may be approximated by $W\Delta v/g$ where W is the frequency in radians/second and Δv is the impact velocity. Since $\Delta v = (2gh)^{1/2}$ where h is the drop height and g is the acceleration due to gravity the transducer output (Q) can be calculated from $Q = (W\Delta v/g) \times 17$ where the factor 17 is the accelerometer charge sensitivity in pC/g. From these relationships the following table is derived.

Drop Height (cm)	g Level	Transducer Output (pC)
8	7.85	133
15	11.0	186
30	15.7	266
60	22.2	376
120	31.4	533

These outputs may be simulated by series voltage insertion into the low side of the accelerometer cable. A T-type adapter may be inserted in the accelerometer cable for this purpose. Voltages may be determined by $V_a = Q/C_a+C_c$ where C_a is the accelerometer capacitance and C_c is the cable capacitance. A nominal value for V_a would be $Q/700+300 = Q \times 10^{-3}$. Thus an input corresponding to an 8 cm drop would be $V_a = 133 \times 10^{-3}$ volts. A low output impedance pulse generator can be used for inputs with pulse width set at 50 msec and rep rate set at 20 ppm. The following sequence could be used for each channel:

Simulated Drop Height (cm)	Number of Pulses	V_a(mv)
8	5	133
	5	−133
15	5	186
	5	−186
30	5	266
	5	−266
60	5	376
	5	−376
120	5	533
	5	−533

Shaping of the signal can be accomplished with capacitive lead and lag elements if a signal close to that produced by the transducer is desired.

Recordings taken in this manner can be used like those generated by an actual drop series as in C.1.

Use of the velocity system would be similar to that of the drop height recording system as presented in Reference 2 with calibration series appearing at the beginning and end of the field shipment tape.

III. Acceleration System

A. Transducer

The transducer used in this system is simply the 2221D accelerometer mounted so that it experiences the full shock of impact. Three mutually perpendicular transducers are used to sense the deceleration components.

B. Electronics

An electronics package (Figure 4) housing the circuitry necessary to condition the transducer signals is connected to the recording unit by a flexible cable. Six operational amplifiers are used per channel making a total of eighteen amplifiers supplied by an integral battery source. The purpose and operation of this circuitry is described below.

The inherent non-linear recording characteristics of magnetic tape are evident from examining curve 2 of Figure 5. Most magnetic tape recording technques use only a portion of the total signal recording range of the tape medium since they operate only on a straight line portion of the input-output curve. In fact, early recorder systems used a smaller gapped recording head (0.1 mil) to produce a greater linearization of the lower portion of the curve indicated in Figure (5) and used only this linear portion of the curve representing about one-half to two thirds of the total signal recording range available. A marked disadvantage of this approach is that use of the smaller gapped recording head increased amplitude errors in the readout. In development of the acceleration recorder system a 0.5 mil gapped recording head was selected to reduce amplitude errors in readout. This increased the nonlinearity of the input-output curve; at the same time, a need to fully use the total signal recording range of the recording medium existed. To solve this problem, the approach used was to record on premagnetized tape which increased the output level by a factor of about 1.5 and to take the accelerometer outputs which are linear with g inputs and amplify these signals by differing amounts in the manner shown in Curve 1, using three stages of linear amplification. The magnetic tape premagnetization procedure is outlined in Reference 4. The curve representing this signal preconditioning matches the input-output characteristics of the recording tape in such a manner that an approximately linear relationship is achieved between the acceleration inputs and the voltage outputs obtained from the tape on readout as indicated in Fig. 5 and as shown in Fig. 6. This approach uses the full signal recording capabilities of the magnetic tape

and provides acceleration data outputs from the recorder which are directly and uniformly affected by amplitude errors in the recording medium over almost the entire signal range.

In summary, this acceleration system electronics (Figure 4) supplies magnetic recording head current that is a nonlinear function of the charge generated by a piezoelectric accelerometer. Extended linear dynamic range of the magnetic tape is realized by utilizing an input to the recorder that compensates for the non-linear behavior of unbiased magnetic tape.

The operational circuitry (see Figures 7, 8) consists of three in-line segments – a charge amplifer, a precision rectifier, and a shaping circuit. The rectifier is two amplifiers – an inverting half-wave rectifier and an inverting summing amplifier. The shaping circuit is three amplifiers – a noninverting clipper, an inverting clipper, and an inverting summing amplifier and is described in detail in the publication attached as an appendix to this report. A transistor trigger circuit is also included in the conditioner for tape recorder activation.

Operation is as follows:

1. Piezoelectric accelerometer supplies a charge input pulse.
2. Charge appears across J1 input terminals and the input of the charge amplifier.
3. A voltage pulse is produced at the output of the charge amplifier equal to the charge input divided by C2.
4. C1 transmits voltage pulse but blocks any D.C. caused by drift of offset.
5. Positive pulses are inverted by the half-wave rectifier and negative pulses are blocked.
6. The sum of the charge amplifier output plus twice the half-wave rectifier output is inverted by the summing amplifier and fed to the shaping circuit. The resulting pulse is equivalent to the absolute value of the charge amplifier output.
7. The rectified pulse is fed to the noninverting clipper, inverting clipper, and one input of the shaper's summing amplifier.
8. The noninverting clipper multiplies the pulse by R12/R11 (511) until its ouput reaches 6.2 volts where it is clipped by D2.
9. The inverting clipper multiplies the pulse by minus (R5+R18)/R4 (minus 4.8) until its output reaches minus 6.2 volts where it is clipped by D2.

10. The sum of R16(R15+R17) (4.32) times the rectified pulse plus R16/R14 (0.0485) times the noninverting clipper output plus R16/R6 (0.75) times the inverting clipper output is inverted by the shaper's summing amplifier and becomes the shaping circuit output as well as the output of the conditioner.

11. The conditioner output pulse is fed to the tape recording head via output connector J2.

12. Simultaneously, the output of the noninverting clipper is A.C. coupled to the transitor trigger circuit, activating the tape recording on the trailing edge of the pulse.

C. Calibration Series

Before and after test shipments the instrumented container should be subjected to calibration series. The results of the drops can be used to interpret the data during shipment.

1. Calibration Drop Test

a. Drop shall be made on an AVCO SM-020 shock machine with the container mounted on the drop table.

b. Drops shall be made on the 2.54 cm thick "A" pad.

c. A minimum of four seconds shall be allowed between drops.

d. The container faces are designated in Figure 3.

e. The drop sequence shall be as follows:

With Face #1 down, drop 3 times each from the following heights: 2 cm, 8 cm, 15 cm, 60 cm, 120 cm.

The drop heights correspond approximately to g levels of 25, 64, 126, 338, and 608, respectively. Actual g levels would have to be checked by an accelerometer mounted on the drop table.

Repeat this test for Faces #2, #3, #4, #5 and #6.

2. Calibration by Voltage Insertion

If you are not equipped to calibrate the accelerometer system by actual drops, input deceleration may be simulated by series voltage insertion into the low side of the

accelerometer cable. As with the velocity system, a T-type adapter may be inserted into the accelerometer conditioning line. Voltage corresponding to deceleration levels may be found by

$$V_A = \frac{Q}{C_A + C_C} = \frac{17 \ \frac{pC}{g}}{(700+300)p^f} = 17 \ \frac{mv}{g}$$

Thus the input range of 5 g to 1000 g may be simulated by inputs of 85 mv to 17 volt. A low output impedance pulse generator can be used with pulse width set between 6 and 25 msec and rep rate lower than 20 ppm. Capacitive lead and lag elements may be used to shape the pulses to conform to actual acceleration pulses. A suggested calibration sequence for each channel follows:

Simulated "g" Level	Number of Pulses	V_a(mv)
±10	5 each polarity	±170
±50	5 each polarity	±850
±100	5 each polarity	±1700
±250	5 each polarity	±4250
±500	5 each polarity	±8500
±1000	5 each polarity	±17000

Recordings can be put on tape in this manner to be used as a reference when the tapes are returned for analysis.

Prototype test results (Figure 6) show that linearity can be assumed over a wide temperature range.

IV. Conclusion

Two systems have been described that use the same sensing elements and recording device.

The low power impact velocity measuring system that can be used to determine package drop heights is a possible alternative to the drop height system described in 72-72-GP (Reference 2) while offering size and weight advantages.

The acceleration system offers wide linear dynamic range while measuring impact deceleration and consuming low power. The tape matching techniques and circuitry could have wide application outside of packaing research.

V. References

1. Nickerson, et. al., "Signal Conditioner for Improved Utilization of Recording Range of Unbiased Magnetic Tape", U.S. Patent No. 3,727,011, April 1973.

2. Nickerson, C.L., "The Drop Height Recording System – A User's Guide", U.S. Army Natick Laboratories Report 72-72-GP, February 1972.

3. Gertel, M. and Franklin, D., "Determination of Container Design Criteria", U.S. Army Natick Laboratories Report 67-50 GP, January 1967.

4. Nickerson, C.L., "The Temperature/Humidity Recording System – A User's Guide, "U.S. Army Natick Laboratories Report 74-21-GP, June 1973.

Shock Recording System with Low-Power IC Operational Amplifiers

C. L. Nickerson
Army Natick Laboratories, Natick, Mass.

Background

A shock recording system was developed utilizing integrated circuit operational amplifiers as basic building blocks to record the impact decelerations experienced by military shipping containers. For this development an existing shipping hazards tape recorder was used by designing a separate signal conditioning unit to couple the acceleration sensors and the recorder. Requirements for this unit were

1. Three parallel data channels.
2. Measurement range of 5 g to 1000 g.
3. Compatibility with existing shipping hazards tape recorder.
4. Operation by battery power.
5. Operational within the temperature range of -50°F to +150°F.
6. Shock limit of 100 g minimum.
7. Six-month unattended lifespan.
8. Error less than ±10% of full-scale.

In addition, the following characteristics were desired:

1. Error less than ±10% of true value.
2. Weight of 5 lbs maximum.
3. Dimensions (maximum): 6" x 7" x 5".
4. Flat response from 30 Hz to 300 Hz.

This paper describes the design and testing of a signal conditioning unit prototype complying with the above requirements.

Input and Output Design Considerations.

The input sensor selected is a piezoelectric accelerometer requiring a charge-to-voltage converter to change the sensor's output to a form easily operated upon. A charge amplifier was designed for this function using an operational amplifier with feedback capacitance large compared to that of the sensor. Leakage resistance is deliberately sustained by a feedback shunt resistor to prevent the amplifier from swinging to saturation. A high resistance was selected to prevent degradation of low frequency response.

The shipping hazards tape recorder uses a Nortronics #5651 recording head writing on motionless Ampex #748 recording tape. The recorder's dynamic range was improved approximately 1.5 times by premagnetization of the tape to saturation; however, bipolar recording was thus rendered impossible making rectification of all incoming signals necessary. Therefore, a precision rectifying circuit having two operational amplifiers was incorporated within the signal conditioning unit to take the absolute value of the charge amplifier output.

The input-output behavior characteristic of the magnetic recording tape is shown by Figure 1, Curve 2. It is apparent that the method to best minimize distortion over the entire dynamic range is to compensate for tape recording non-linearity by a matching system characteristic. Figure 1, Curve 1 shows how this can be done effectively by

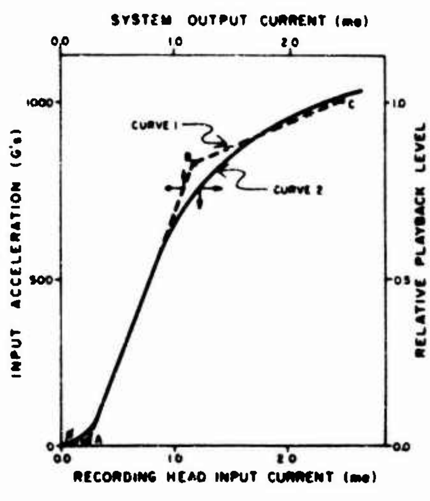

Figure 1. Input-Output Design Curves.

three straight-line segments. Circuitry for synthesizing this characteristic is shown in Figure 2. Three operational amplifiers are used with break points determined by Zener diodes. It was found that diode D1 could not be directly connected to the output of amplifier A1 because a direct connection caused distortion below the Zener breakdown voltage by shunting the large feedback resistor and distortion above the breakdown voltage by permitting the follower behavior of the non-inverting configuration to effect system output. Amplifier A2 is an inverting amplifier with a relatively low feedback resistance so that insertion of diode D2 across the feedback path can be allowed. Required resistance ratios for this shaping circuit were determined by the method shown in the Appendix.

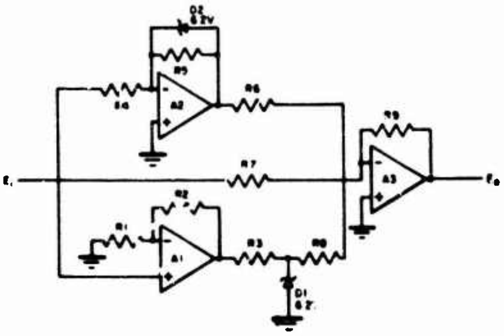

Figure 2. Shaping Circuit.

Activation of the tape recorder to provide for tape transport following input levels of 3 g or greater is accomplished by ac coupling of the output of amplifier A1 to a two-transistor switch similar to a Schmitt Trigger. The transistors are the only active components in this system besides the eighteen operational amplifiers in the three data channels.

Figure 3 presents a block diagram of the total acceleration recording system. The signal conditioning unit or package includes the charge amplifier, precision rectifier, and shaping circuits together with the power supply necessary for their operation.

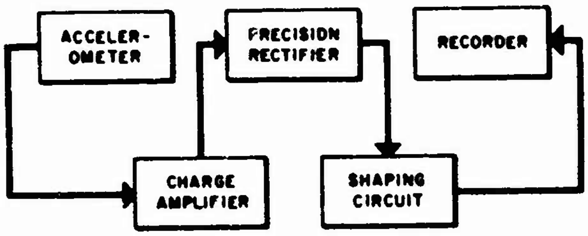

Figure 3. Block Diagram - Acceleration Measuring System.

Time and Temperature Design Considerations.

The lifespan of this system is limited by the characteristics of the power supply and the system power drain. Power drain is largely quiescent drain in this system because inputs are of short duration and widely spaced, and the system cannot be turned on or off during its lifespan. National Semiconductor NH0001 was chosen as the operational amplifier to be used because of its low quiescent drain (less than 100 uA) and its operational temperature range (-55°C to +125°C).

Alkaline cells were chosen for power because of their superior temperature characteristics; however, their discharge characteristic is far from flat, and allowance must be made for change in voltage. Plus and minus 12 volts power was chosen to allow a six-month discharge to approximately ± 8 volts, at which point the maximum output swing of NH0001 devices is typically about 1.5 volts lower with diode clamping (± 6.5 volts) thus remaining greater than 6.2 volts, the required output for the breakpoint diodes.

The charge amplifiers' output exhibited dc drifting with time and temperature that could not be tolerated. That drift could have been reduced by decreasing the shunt resistance in the feedback path; however, low frequency response would have suffered. It was decided to ac couple the charge amplifier to the rest of the system with a large capacitor.

Care was taken to insure that discrete components critical to the operation of the system would not be grossly affected by temperature. Polystyrene capacitors were used as feedback elements in the charge amplifier, metal film resistors were used where needed, and 0.005%/°C reference diodes were used as the breakpoint devices.

Fabrication and Testing of the Signal Conditioning Unit.

After completion of system design and successful breadboard testing, a prototype was fabricated by the Integrated Electronics Division of the Electronics Components Laboratory, U. S. Army Electronics Command (see Figure 4).

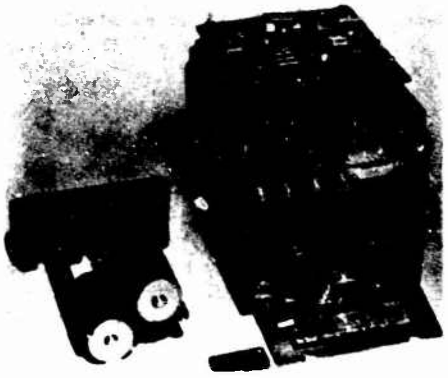

Figure 4. Signal Conditioning Unit.

This unit has the following measured characteristics:

1. Weight: 4 lb 11 oz
2. Dimensions: 4-1/8" x 4-1/2" x 3-1/2"
3. Power: ±12 volts
4. Quiescent Drain: ±1.275 ma, -0.9 ma (18 op amps total)

A test program using the prototype was conducted at U. S. Army Natick Laboratories covering the entire range of inputs at standard conditions and at the temperature extremes. The unit was subjected to repeated g levels between 100 and 200 during these tests and was not damaged. Results of these tests are shown in Figure 5, each plotted point being the average of five successive inputs generated by drops of equal height on the same surface. Errors much greater than 10% were found only during the low temperature test for input g levels below four hundred. A change in the bandwidth of the system was thought to be the cause; however, upon testing, the frequency range of the system was found to be flat from 10 Hz to 300 Hz over the entire temperature range (-50°F to +150°F). The low temperature errors were considered tolerable so further work to pinpoint the cause was abandoned.

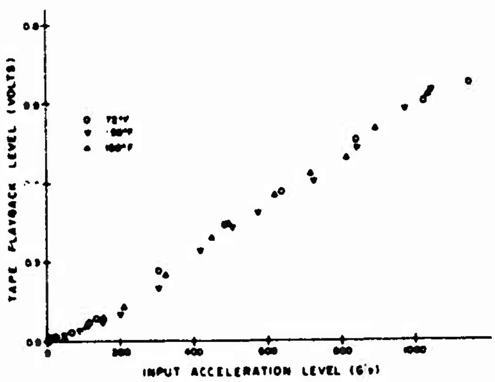

Figure 5. System Performance.

The only requirement that was not tested was the lifespan which was estimated to be 4500 hours (approximately six months) by using alkaline cell discharge characteristic curves and the measured quiescent current drain.

Acknowledgements.

The author thanks USAECOM for their assistance in this development. Particularly appreciated is the advice given by R. Reitmeyer regarding special precautions necessary when using IC operational amplifiers and his help during the prototype fabrication phase. Gratitude is also extended to R. Sproat, H. French, and J. Van Dover of USAECOM. The dynamic range requirement would not have been met without Dr. L. A. McClaine's solution of matching the premagnetized tape recording characteristic by three straight-line segments. Dr. McClaine and F. D. Barca, both of Natick Laboratories, are thanked by the author for their many contributions throughout this development.

Conclusions.

All requirements were met by this system and most desired characteristics were attained. The key to success in this project was the use of low power integrated circuit operational amplifiers. Their low quiescent current permitted six amplifiers per channel without excessive battery weight and size. Flexibility of design thus attained facilitated the required solution.

APPENDIX

Shaping Circuit Design Calculations.

Resistance ratios required by the shaping circuit of Figure 2 can be calculated with reference to the points Ø, A, B, and C of Curve 1, Figure 1.

Let I_H = recording head input current,
E_o = system output voltage,
E_i = shaping circuit input, and
V_Z = Zener breakdown voltage.

Make I_H in milliamperes equal to E_o in volts by taking R = 1000 ohms.

$$(R9/R7) = \text{Slope } \overline{BC} = \frac{E_{oC} - E_{oB}}{E_{iC} - E_{iB}} \quad (1)$$

$$\text{At B,} \quad E_{iB}\,(R5/R4) = V_Z \quad (2)$$

$$\text{thus} \quad (R5/R4) = (V_Z/E_{iB}) \quad (2a)$$

$$\text{Slope } \overline{AB} = (R9/R7) - (R9/R6)(R5/R4) = \frac{E_{oB} - E_{oA}}{E_{iB} - E_{iA}} \quad (3)$$

$$\text{thus} \quad (R9/R6) = \frac{E_{iB}}{V_Z}\left[\frac{E_{oC}-E_{oB}}{E_{iC}-E_{iB}} - \frac{E_{oB}-E_{oA}}{E_{iB}-E_{iA}}\right] \quad (3a)$$

$$\text{At A,} \quad E_{iA}\,(R2/R1) = V_Z \quad (4)$$

$$\text{thus} \quad (R2/R1) = (V_Z/E_{iA}) \quad (4a)$$

$$\text{Slope } \overline{ØA} = (R9/R7) - (R9/R6)(R5/R4) + (R9/R8)(R2/R1) = (E_{oA}/E_{iA}) \quad (5)$$

$$\text{thus} \quad (R9/R8) = \frac{E_{iA}}{V_Z}\left[\frac{E_{oA}}{E_{iA}} - \frac{E_{oB}-E_{oA}}{E_{iB}-E_{iA}}\right] \quad (5a)$$

This paper reports research undertaken at the U. S. Army Natick (Massachusetts) Laboratories and has been assigned No. TP-801 in the series of papers approved for publication. The findings in this report are not to be construed as an official Department of the Army position.

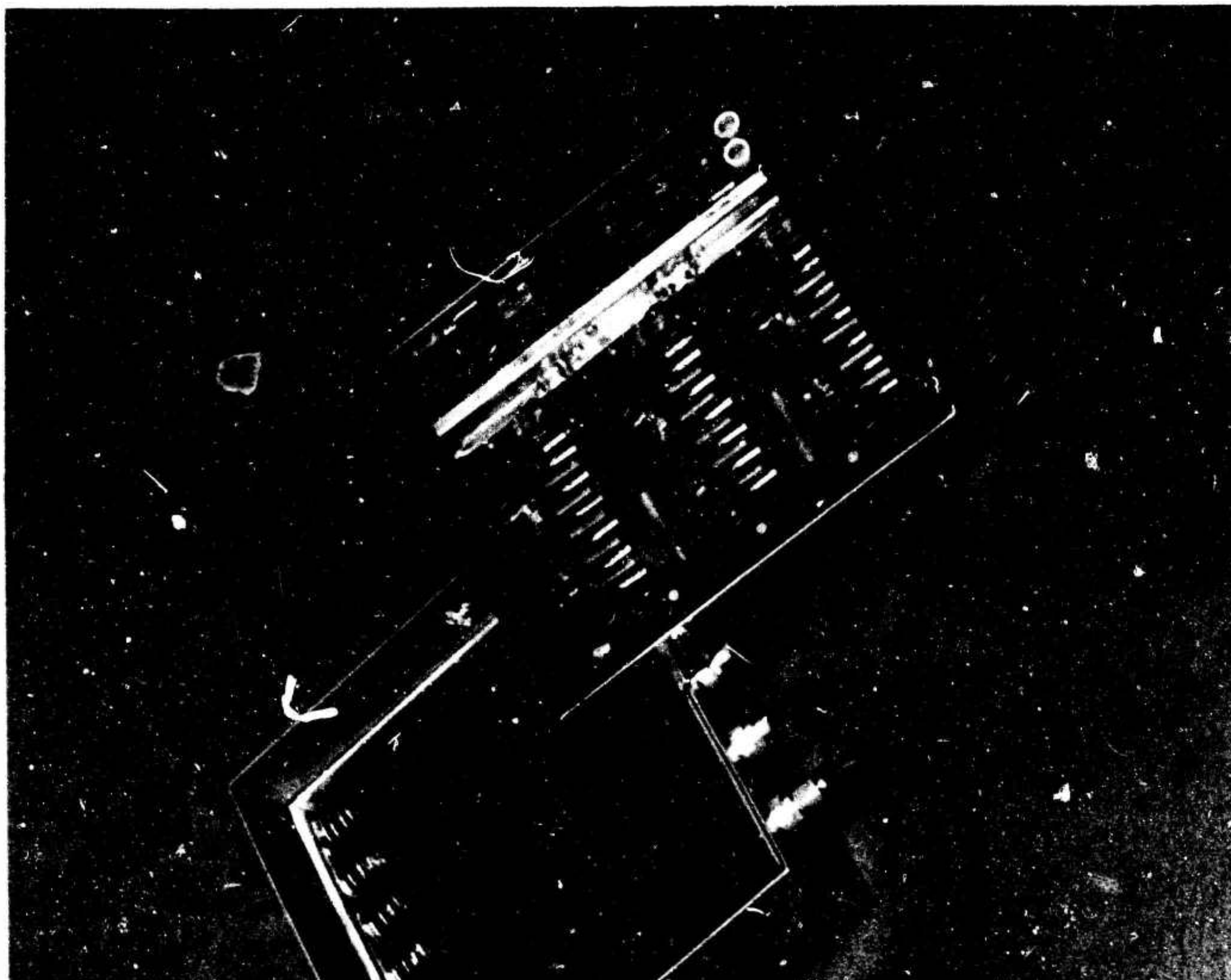

Figure 1
Velocity Assem Electronics Package

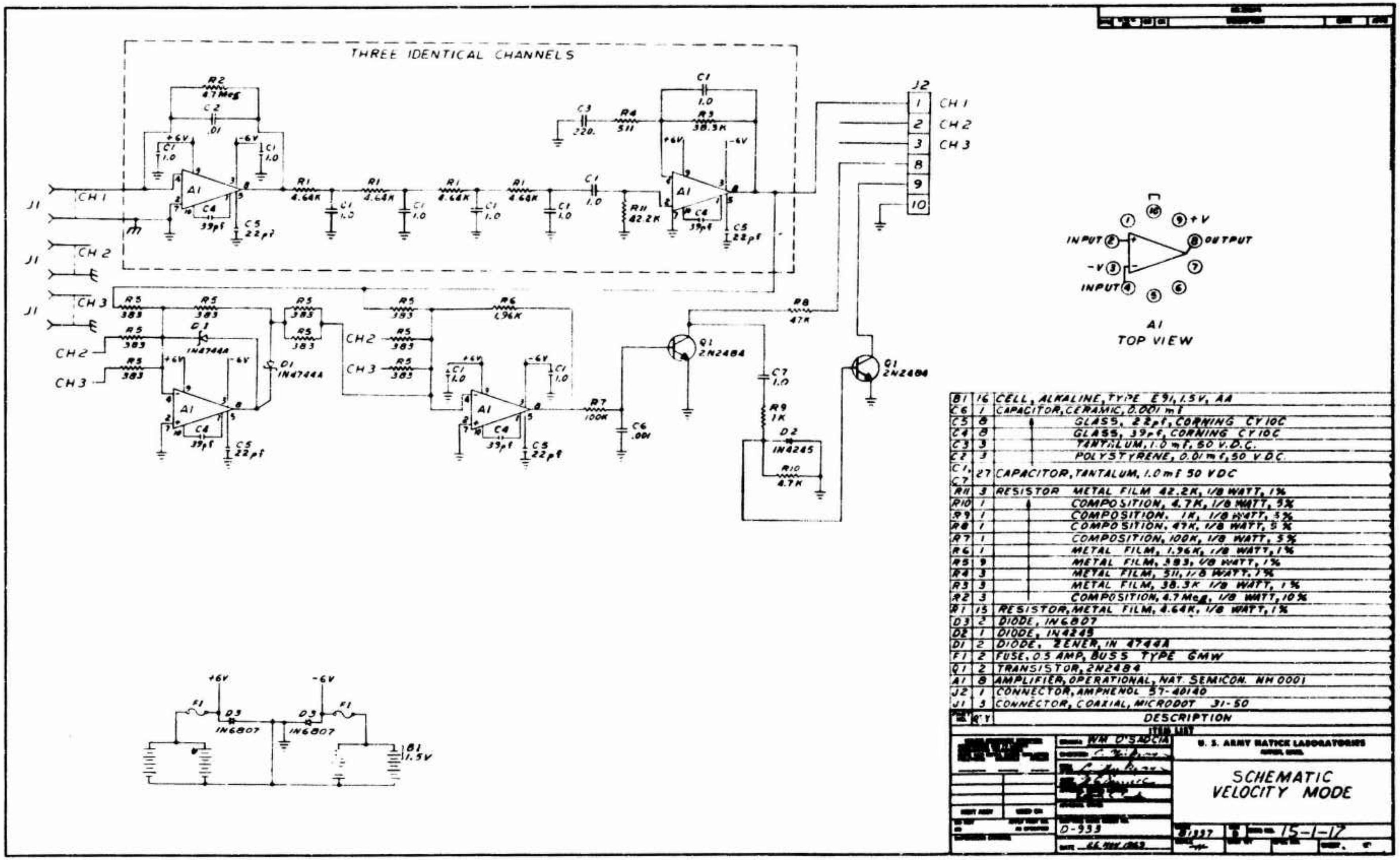

Figure 2

Velocity System Schematic

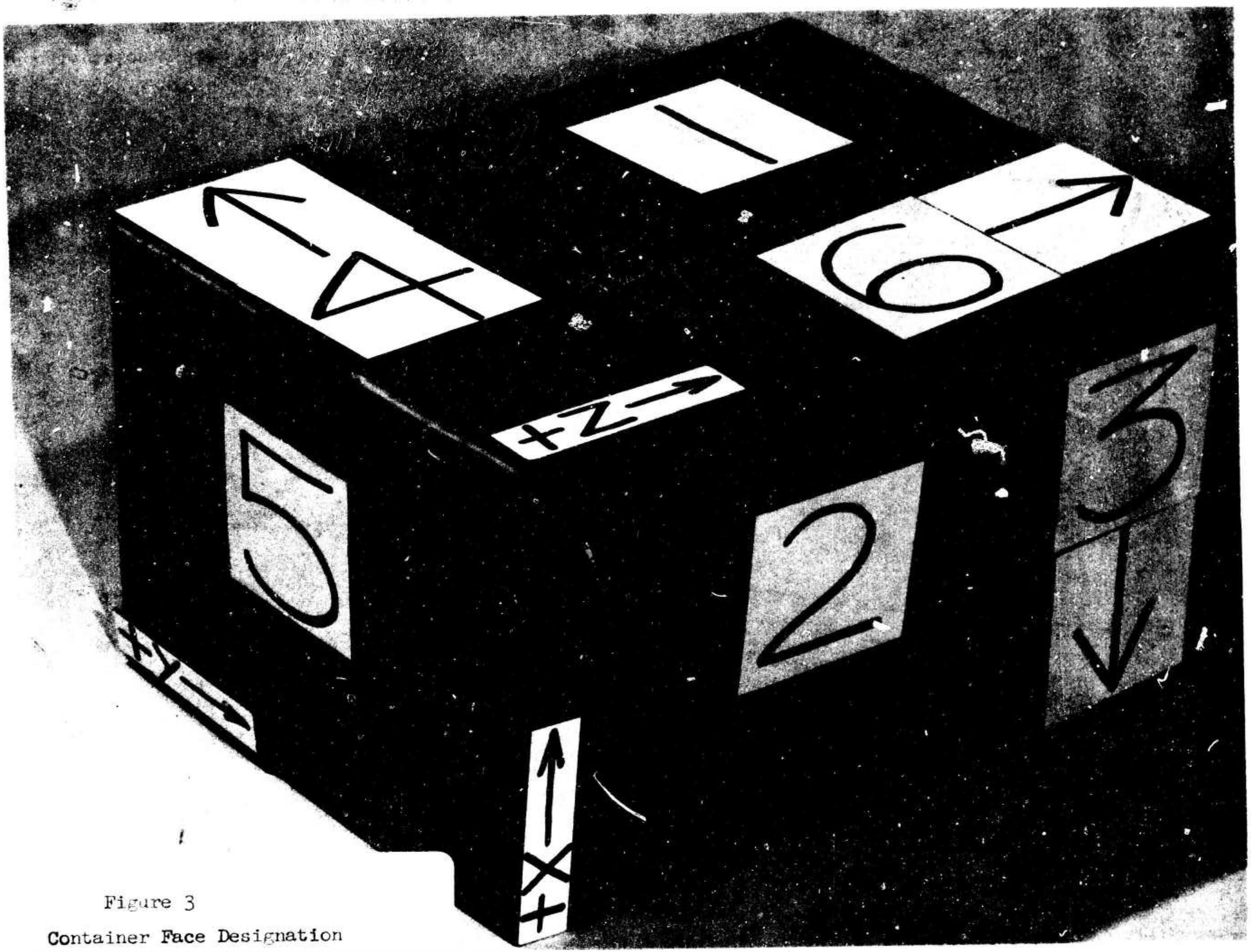

Figure 3
Container Face Designation

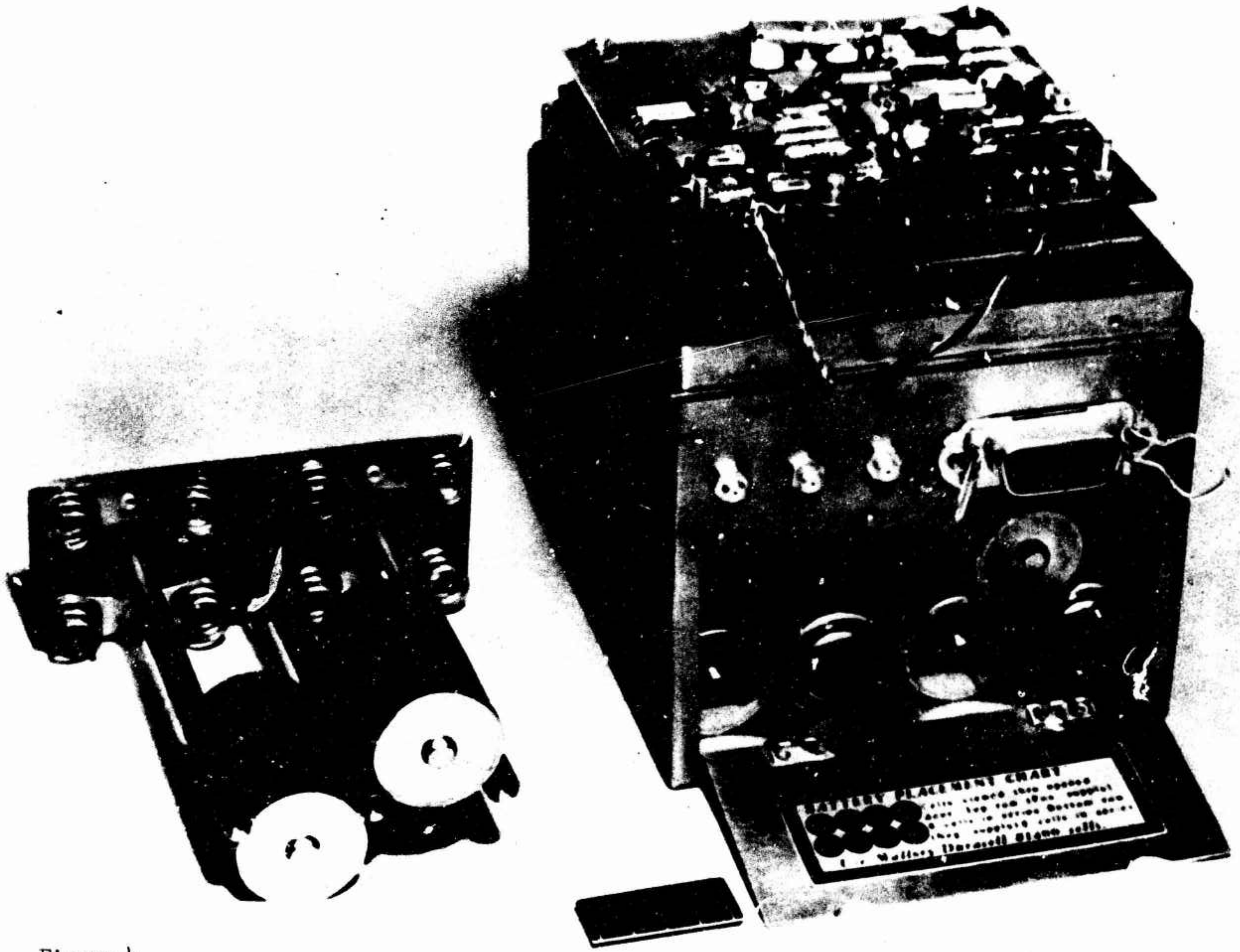

Figure 4
Acceleration System Electronics Package

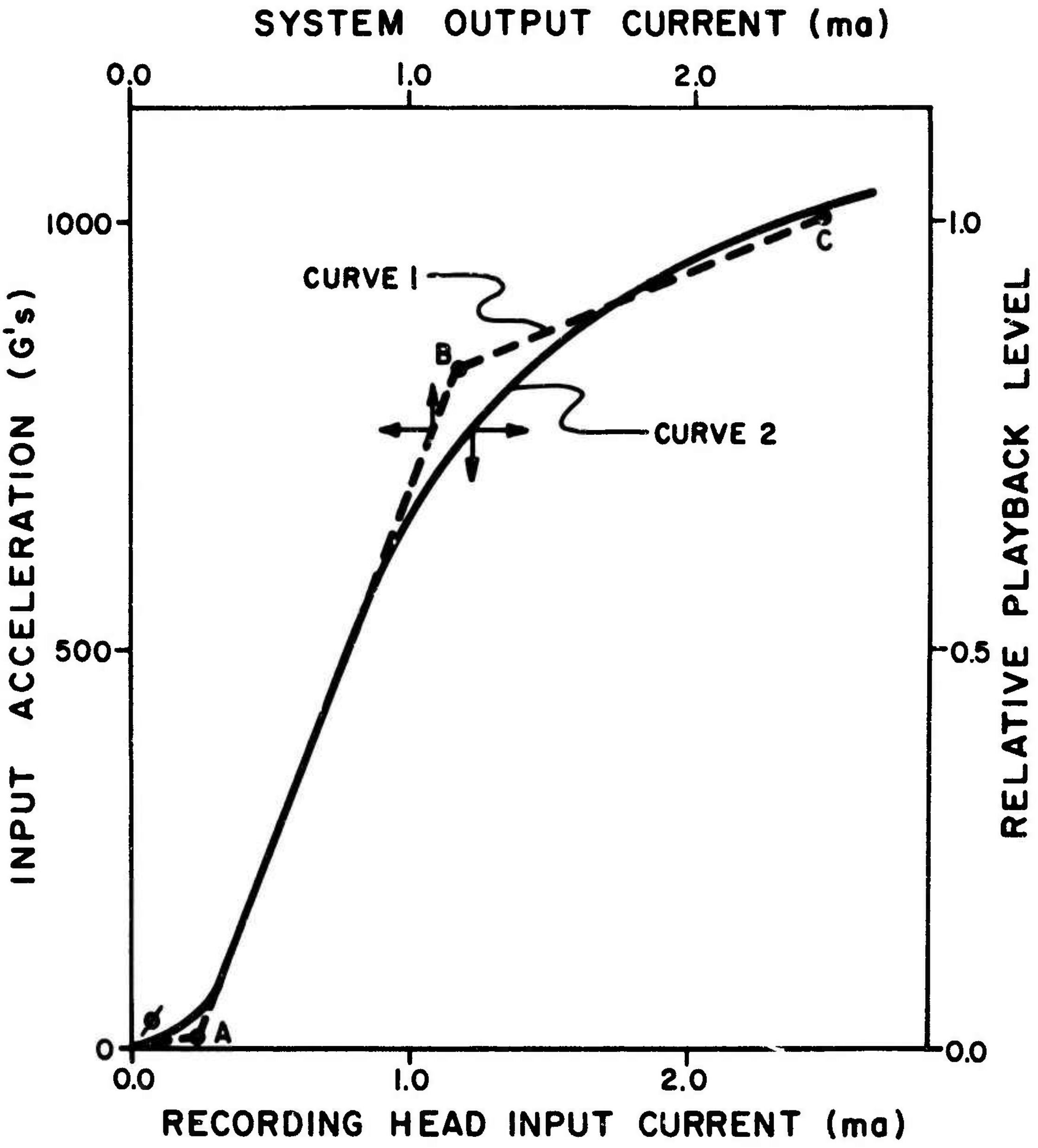

Figure 5

Input-Output Design Curves

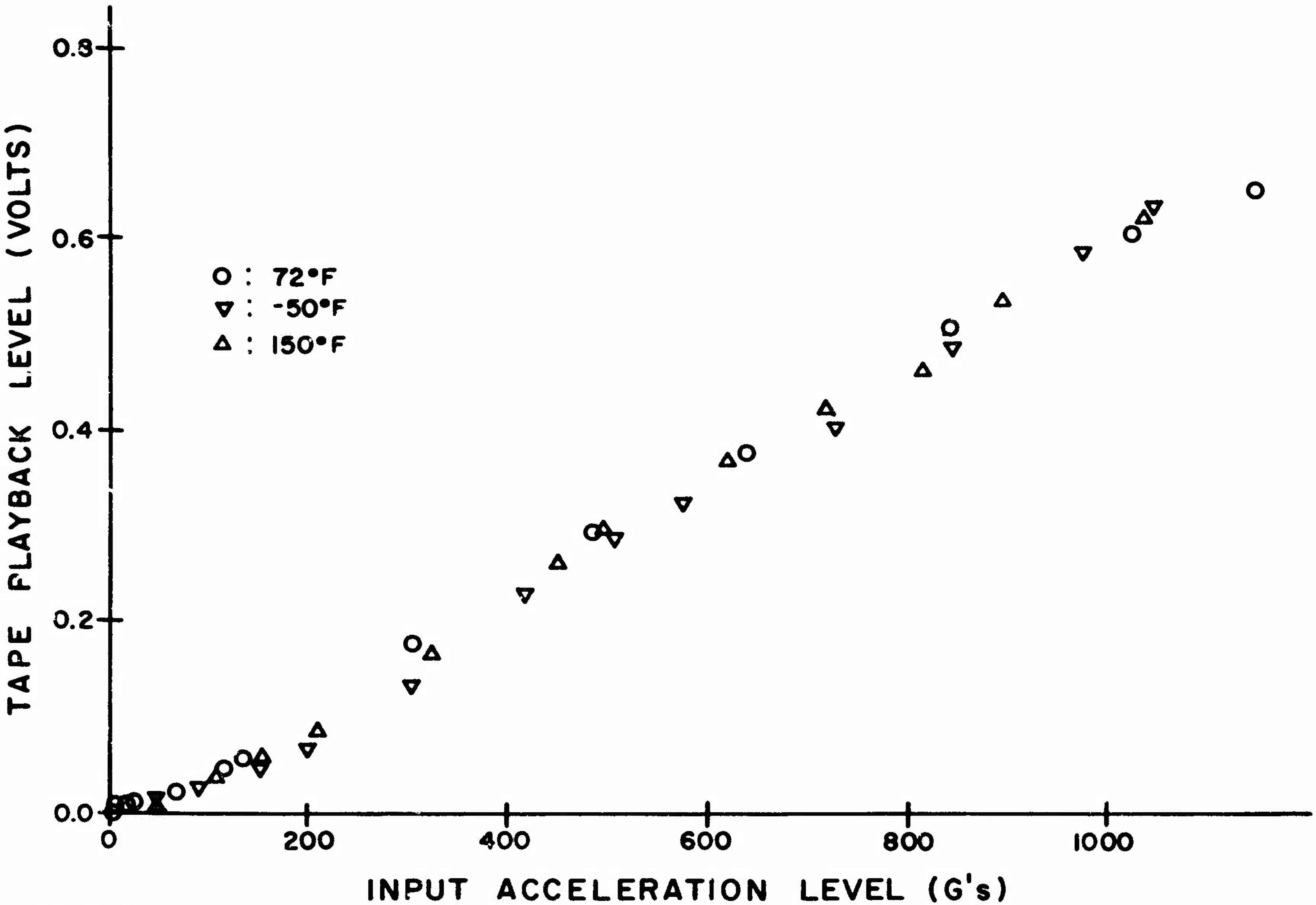

Figure 6

System Test Results

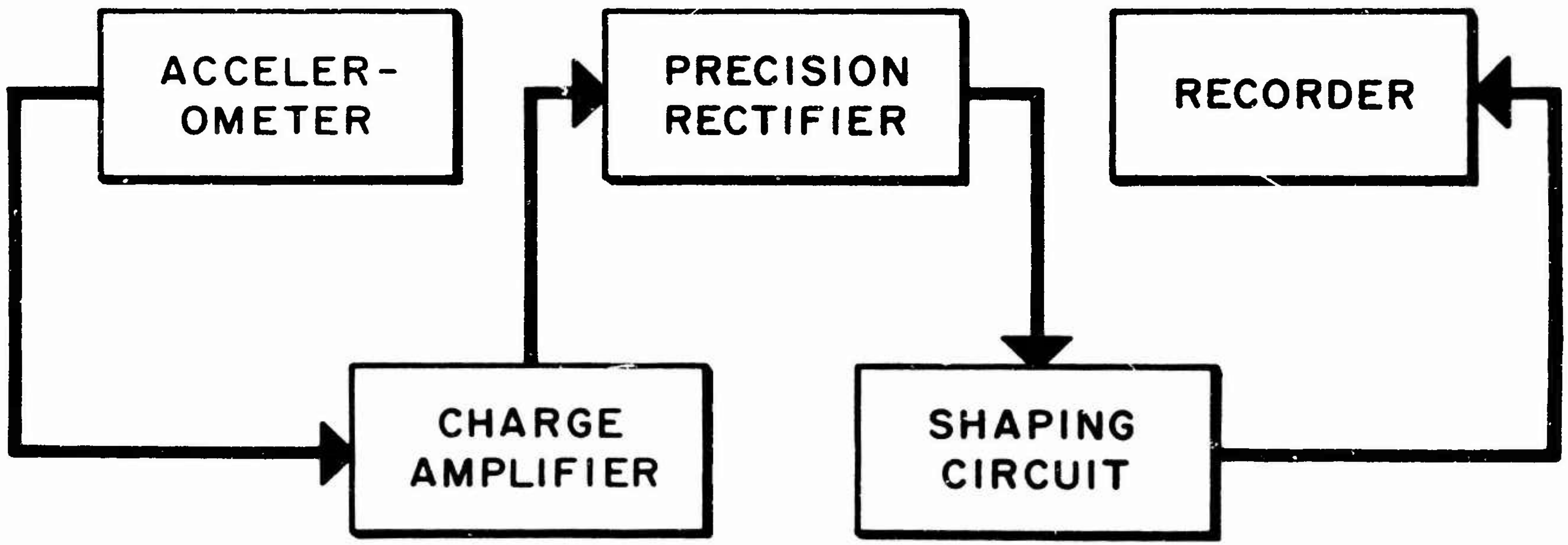

Figure 7

Block Diagram-Acceleration Measuring System

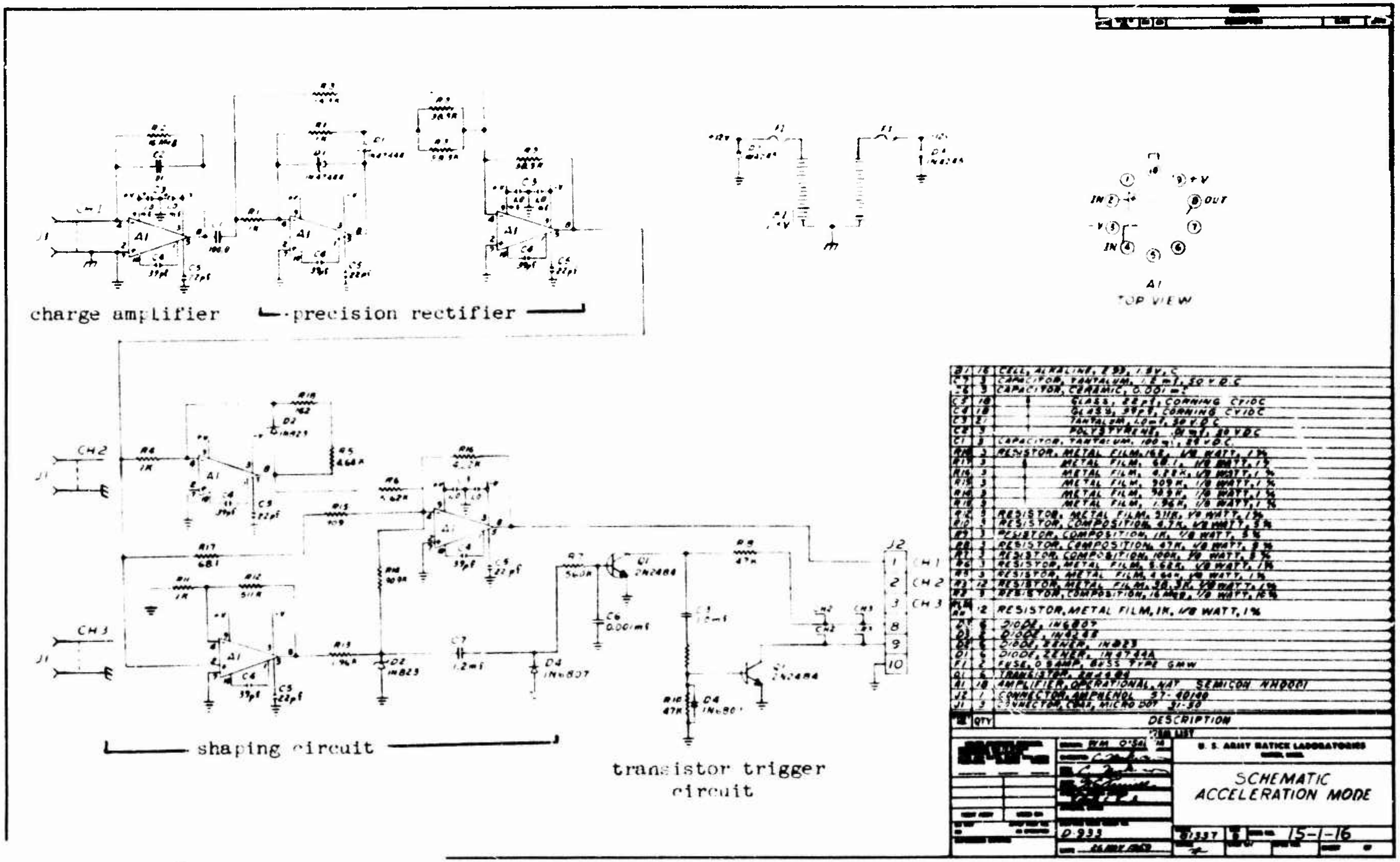

Figure 8

Acceleration System Schematic